

# Main sequence stars with asymmetric dark matter

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We study the effects of feebly or non-annihilating weakly interacting Dark Matter (DM) particles on stars that live in DM environments denser than that of our Sun. We find that the energy transport mechanism induced by DM particles can produce unusual conditions in the core of Main Sequence stars, with effects which can potentially be used to probe DM properties. We find that solar mass stars placed in DM densities of  $\rho_\chi \geq 10^2 \text{ GeV/cm}^3$  are sensitive to Spin-Dependent scattering cross-section  $\sigma_{SD} \geq 10^{-37} \text{ cm}^2$  and a DM particle mass as low as  $m_\chi = 5 \text{ GeV}$ , accessing a parameter range weakly constrained by current direct detection experiments.

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*Introduction*— Identifying the Dark Matter (DM) is one of the most enthralling problems of modern cosmology and particle physics. Weakly Interacting Massive Particles (WIMPs) are among the most popular candidates and are currently searched for with different strategies, see e.g Ref. [1] for reviews. The effects of WIMPs on stars have been recently investigated as possible additional probes for DM searches: in presence of self-annihilations, WIMPs captured inside a star can provide an exotic source of energy. Whereas the effects on the Sun are negligible because of the small DM density in the solar neighborhood, they may be remarkable on stars living in dense DM environments such as the Galactic Center, or the first halos to harbor star formation at high redshift [2–5]. In general, indirect searches of DM would fail for very feebly annihilating DM candidates. This is the case, for instance, of many asymmetric DM (ADM) models (see e.g.[6]), where DM annihilations may not occur in presence of an asymmetry between DM particles and antiparticles. Still, these particles accumulated in a star can scatter off nuclei and transport energy within its bosom. This effect results in a modification of the density and temperature profiles which can lead to detectable changes of the solar neutrino fluxes and gravity modes [7–10]; more compact objects like neutron stars may cumulate enough particles to reach the Chandrasekhar mass and drive the collapse of a central black hole, [11, 12]. Stellar physics can thus provide a strategy to indirectly test this class of models. Interestingly, the evolution of Main Sequence, solar mass stars placed in environments with higher ADM densities has not been studied yet (while this paper was being refereed, a recent study addressing very low-mass stars in ADM has been published, [13]). Here we address this topic, showing that the energy transport induced by ADM cumulating inside such stars can provoke dramatic effects on the

stellar structure.

Whether DM particles are actually intrinsically “asymmetric”, or if their self-annihilation rate in stellar environment is low enough ( $\langle \sigma v \rangle \lesssim 10^{-33} \text{ cm}^3/\text{s}$  for the Sun) is indistinguishable for its effects in stellar evolution, [9]; hereafter our definition of “asymmetric” embraces the previous condition.

*ADM in stars*— Here we adopt the same formalism as in [9], to which we address the reader for details. A thorough description of the underlying theory can be found also in [2] and references therein. DM particles can be captured by a star via scattering off nuclei, the evolution of the total number of DM particles  $N_\chi$  inside the star reading:

$$\dot{N}_\chi = C - 2AN_\chi^2 - EN_\chi \quad (1)$$

where  $C$  is the particle capture rate over the star,  $A$  is the annihilation rate and  $E$  the evaporation one. For the asymmetric DM candidates we are considering, the annihilation rate is null and evaporation is negligible for the physical conditions on which we focus, equation 1 therefore becomes trivial for ADM. Here we recall the linear dependence of the capture rate on the spin-dependent scattering cross section  $\sigma_{SD}$  and the environmental DM density  $\rho_\chi$ . Captured particles keep on scattering with the stellar gas reaching a thermally relaxed distribution inside the star,  $n_\chi(r) = n_{\chi,0} e^{-r^2/r_\chi^2}$ . For the DM masses and cross sections we are going to consider, in a Sun-like star the thermal DM radius  $r_\chi$  is of the order of  $r_\chi \lesssim 10^9 \text{ cm}$  ( $\sim 0.03 R_\odot$ ), thus making DM particles confined within the nuclear energy generation region. DM particles weakly interacting with the baryons provide an energy transport mechanism, additional to the standard ones. In their orbits, DM particles scatter in the innermost regions (called the “inversion core” hereafter) absorbing the heat and releasing it in the immediate sur-

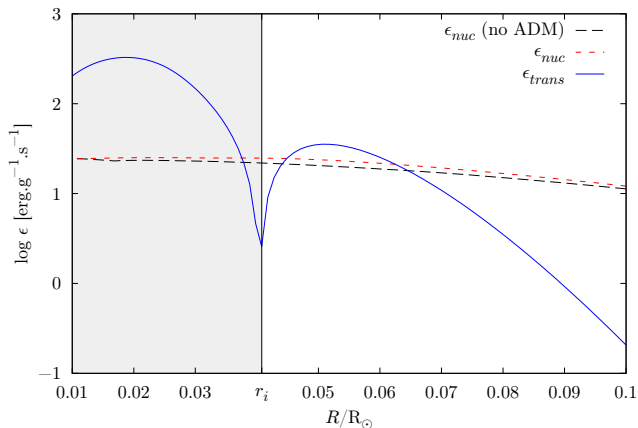


FIG. 1: The structure of  $\epsilon_{trans}$  and  $\epsilon_{nuc}$  for  $1M_{\odot}$  star evolved with the ADM parameters  $\rho_{\chi}=10^3 \text{ GeV/cm}^3$ ,  $\sigma_{SD}=10^{-37} \text{ cm}^2$ ,  $m_{\chi}=10 \text{ GeV}$ . The profile is taken when the central hydrogen fraction,  $X_c=0.2$ . Also shown for comparison is  $\epsilon_{nuc}$  of a star evolved without ADM, at the same age. The shaded area -innermost of  $r_i$ - shows where  $\epsilon_{trans}$  has negative sign, thus absorbing energy from the stellar gas.

roundings, within the nuclear energy production region.

*Stars in high ADM densities*— The effects of the DM energy transport is enhanced for increasing DM densities since the number of particles cumulated inside the star grows linearly with  $\rho_{\chi}$  (see the Appendix for a short discussion on this). Hence, we have studied the evolution of a solar type star ( $1M_{\odot}$ ,  $X=0.72$ ,  $Y=0.266$ ,  $Z=0.014$ ) for increasing DM densities. In this section we fix the DM-proton spin dependent cross section  $\sigma_{SD}=10^{-37} \text{ cm}^2$  and DM particle mass  $m_{\chi}=10 \text{ GeV}$ . We will discuss the effect of varying these parameters in the following sections, whereas we keep the stellar velocity through the DM halo  $\bar{v}=220 \text{ km/s}$ .

We have modified the publicly available DarkStars code [14], in order to use the Spergel & Press formalism (Eq. 4.9 in [15]) rather than the Gould & Raffelt one, [16]. Whereas the latter has been proved to correct the overestimate -of order unity- present in the previous formalism, we have noticed that in critical conditions such as the ones we meet in our study the implementation of this formalism may easily induce a unphysical behavior of the solution obtained by numerical codes. We have found this numerical artifact to show up both with the original DarkStars code and the GENEVA stellar evolution code [17], modified for the inclusion of DM effects, as we have described in [9]. The effects we describe in the following could therefore be overestimated of a factor unity, namely they could show up for DM densities  $\rho_{\chi}$  a factor unity bigger than the actually quoted ones.

We evolve the star from the Zero Age Main Sequence, by adopting an environmental  $\rho_{\chi}=10^3 \text{ GeV/cm}^3$ , which for a NFW DM density profile corresponds to  $R_{gal} \sim 10 \text{ pc}$  from the Galactic center. As long as the absolute value of the DM transport energy term  $\epsilon_{trans}$  is much smaller

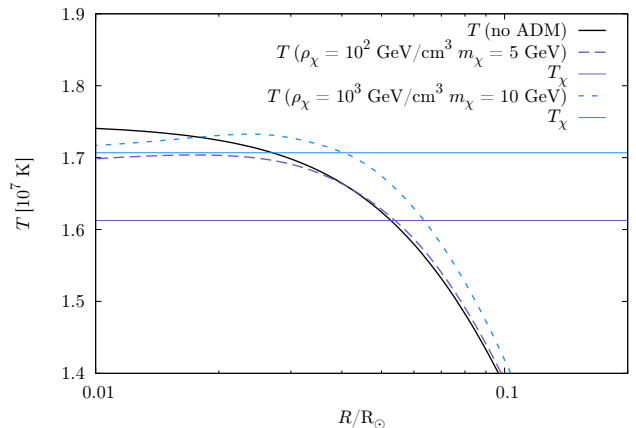


FIG. 2: Stellar (baryonic) temperature profile for two ADM parameter set, as from the plot; the solid black line is a model evolved without DM. The profile is taken when the central hydrogen fraction,  $X_c=0.2$ . This corresponds at an age of approximately 5.3, 5.4, and 5.6 Gyr for the case with no ADM, and increasing ADM density  $\rho_{\chi}$ , respectively.

than the nuclear energy generation term  $\epsilon_{nuc}$ , the global properties of the star are not modified. We have verified that the central temperature and density profile *are* altered with respect to the same star evolved without DM, according to what we have seen in [9]: neutrino fluxes and seismic g-modes of the star *get* modified with respect to the standard case and we defer a systematic analysis of this to later studies.

Here we focus on a much more dramatic effect, taking place when  $\epsilon_{trans}$  becomes comparable with  $\epsilon_{nuc}$ . For our choice of DM parameters  $m_{\chi}$  and  $\sigma_{SD}$  this takes place when the total population of DM particles in the star,  $n_{tot} \sim 5 \times 10^{47} \#$  (for this particular choice of parameters and stellar mass, this takes place approximately 5 Gyr after the Zero Age Main Sequence). In this conditions DM is able to transport out of a very central region the entire energy generated by nuclear reactions, thus resulting in an efficient sink of energy for the stellar region within the inversion radius  $r_i \sim 0.04 R_{\odot}$ , namely the region where the isothermal WIMP temperature is lower than the local baryonic temperature,  $T_{\chi} < T_b$ . Outside of  $r_i$ , yet within the nuclear energy generation region  $r_{nuc} \sim 0.1 R_{\odot}$ , DM particles deposit the energy absorbed from the innermost, hotter baryons into the local medium, colder than  $T_{\chi}$ . This energy deposit is not crucial: what matters most is the effective diminished efficiency of the nuclear energy source at the center. The star is forced to compensate for this decrease by increasing the nuclear energy production outside the inversion core. In Figure 1 we show the radial structure of  $\epsilon_{trans}$  compared to  $\epsilon_{nuc}$ : it is clearly visible how the DM energy transport is the mechanism dictating the energetics of the region within the inversion radius  $r_i$ , and the energy sink caused by DM in this region induces a temperature drop. An example of the resulting temperature profile is shown in Figure 2, where both the central

drop within  $r_i$  caused by the ADM energy absorption, and a raise in the shell between  $r_i$  and  $r_{nuc}$  are clearly visible. Such new temperature profile is the result of the new equilibrium reached by the star, which readjusts its structure in order to provide the correct energetics; the new nuclear reaction rate  $\epsilon_{nuc}$  is visible in Figure 1. These modifications are quite remarkable, modifying the chemical evolution of the star as well as its external appearance, see more in the next Section.

The behavior we have described is reached when DM particles are enough that  $\epsilon_{trans} > \epsilon_{nuc}$  in the central region of the star, within  $r_i$ . For the value of *environmental* DM density  $\rho_\chi = 10^3 \text{ GeV/cm}^3$  and  $\bar{v} = 220 \text{ km/s}$  adopted in this run, this happens quite early during the evolution of the star, whereas for DM densities smaller than  $\rho_\chi = 10^3 \text{ GeV/cm}^3$  (with  $m_\chi = 10 \text{ GeV}$ ), the time needed for the star to capture enough particles is longer than the MS itself, so the mechanism we have described can not take place. Conversely, for increasing DM densities  $\rho_\chi$  (and therefore the capture rate  $C$ ) this arrives at shorter times during the Main Sequence.

We have evolved several stellar models for different values of the environmental DM density (keeping constant  $\sigma_{SD}$  and  $m_\chi$ ), finding that remarkable effects on the stellar structure are present for different DM densities  $\rho_\chi$ . It is worthwhile to remark that for increasing  $\rho_\chi$ , DM particles start being an effective sink of energy at decreasing times. The cumulation of more particles during the MS boosts the  $\epsilon_{trans}$  increasingly, with even more remarkable effects: in Figure 3 we show the impact of increasing ADM densities on the star's evolution. Whereas for  $\rho_\chi \lesssim 10^4 \text{ GeV/cm}^3$   $|\epsilon_{trans}| > \epsilon_{nuc}$  for  $R \lesssim r_{nuc}$ , its integral over the whole star is smaller than the total nuclear luminosity of the star,  $L_{trans} \equiv \int |\epsilon_{trans}| dV < L_{nuc}$ : the structure reacts to it by finding a new stable configuration at increased luminosities, by readjusting the nuclear reaction rate between  $r_i$  and  $r_{nuc}$ . On the other hand, at very high ADM density ( $\rho_\chi \gtrsim 10^5 \text{ GeV/cm}^3$ ) the temperature is mitigated in the whole nuclear energy generation region, rather than only in the inversion core. This is because the energy reinjected by the WIMPs at  $R > r_i$  is now sufficient to inflate that region, thus cooling it and reducing the efficiency of  $\epsilon_{nuc}$ . The envelope then contracts to extract energy from the gravitational potential well.

Summarizing, when  $L_{trans} < L_{nuc}$ : the star compensate for the deficit of nuclear energy generation in the center by increasing the nuclear energy generation outside the inversion core. At  $L_{trans} > L_{nuc}$ : the redistribution of the energy by the WIMPs is such that  $\epsilon_{nuc}$  is reduced in the whole nuclear core and the star must compensate this deficit by the contraction of its envelope.

*Diagnostic power*— Is it possible to use such mechanism as a possible probe for ADM parameter space, namely: are stellar observables affected from this mechanism at a testable level? Deviations from the standard path in the Hertzsprung-Russell (HR) diagram are the ideal observable.

The modifications of the stellar structure described in the previous section, induced by ADM, are clearly visible in the HR diagram. In our Figure 3 it is possible to see how the model described above detaches from a normal path in the temperature-luminosity plane once captured DM particles have achieved the right number  $n_{tot}$ . The new distribution of temperature makes the star more luminous and bigger, thus moving left and upward in the plane for low ADM densities. The resulting position of the star in the HR diagram is therefore unusual, and more so as the star ages and gets toward the end of the MS. In Figure 3 it can be appreciated how by increasing  $\rho_\chi$  the actual position of the star in the HR changes, finally reverting it to lower luminosities as a consequence of the dramatic drop in temperature, as explained in the previous Section; still, these stars are kept away from the usual track. This could indeed be used to identify a peculiar generation of stars, and probe ADM parameters or the distribution of ADM in our Galaxy. However, we caution that these observational tests are challenged by the difficulty of observing stars close to the galactic center (or in the very center of Dwarf Galaxies, where DM environmental conditions could be similar), which makes current uncertainties on the position of these stars in the HR diagram quite large.

However, it is worth to remark that, unlike the case of annihilating DM, the effects of ADM may be “portable” by the star throughout its journey in space. In the case of DM annihilating and providing an additional energy source to the star, the effects are tightly related to the environmental DM density the star is experiencing within the short equilibrium time  $\sim \mathcal{O}(10^6 \text{ yr})$ . Self-annihilation depletes the DM cumulated inside the star, and a continuous provision is required to keep the effects going, [2]. ADM does not escape from the star: in principle stars may capture ADM in a dense environment and migrate somewhere else in the Galaxy, and the effects would still be visible.

*The effect of varying DM parameters*— For the values of  $\sigma_{SD}$  we are considering, the DM energy transport is non local, i.e. the DM free path is larger than  $r_\chi$  and DM particles can efficiently transport energy between distant regions in the stellar core. In this case,  $\epsilon_{trans}$  is enhanced for larger  $\sigma_{SD}$ , until the DM energy transport becomes local and so  $\epsilon_{trans}$  is decreased, this happening for  $\sigma_{SD} \gtrsim 10^{-34} \text{ cm}^2$ . Capture of DM particles is easier for lighter ones, and heavier DM particles tend to be confined in smaller regions inside the core, both effects making the DM transport inside stars more sensitive to small values of  $m_\chi$ .

For  $m_\chi = 10 \text{ GeV}$  and  $\sigma_{SD} = 10^{-38} \text{ cm}^2$  the dramatic effects on the stellar structure which we have previously discussed start to appear for  $\rho_\chi \gtrsim 10^5 \text{ GeV/cm}^3$ . This actually demonstrates that smaller SD cross sections can be explored, although the price to pay is to shrink the region of the Galaxy potentially probing this mechanism. On the other hand, for  $\sigma_{SD} = 10^{-36} \text{ cm}^2$  the same situation is reached at lower DM densities,  $\rho_\chi = 10^2 \text{ GeV/cm}^3$ .

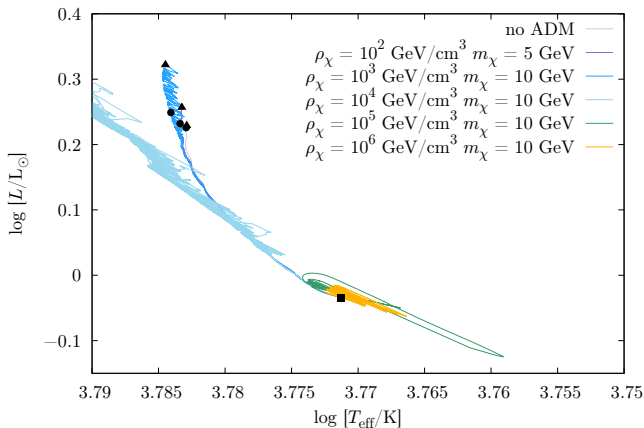


FIG. 3: The Hertzsprung-Russell diagram for  $1M_{\odot}$ , for varying DM parameters as marked in the plot, with  $\sigma_{SD}=10^{-37}\text{cm}^2$ . The solid black square is the starting point of our simulation, black solid circles mark an age of 6Gyr, not achieved for runs with  $\rho_{\chi} > 10^3\text{GeV}/\text{cm}^3$ . Black solid triangles mark the fall of central hydrogen fraction  $X_c$  below 0.1. This takes place at an age of 6.05, 6.36, and 6.39 Gyr for the no ADM case,  $\rho_{\chi}=10^2, 10^3\text{GeV}/\text{cm}^3$ , respectively. Notice that the fluctuations may be numerical artifacts, see Appendix for details.

For smaller DM masses (but still above the evaporation mass  $\sim 5\text{GeV}$ ) it is possible to probe smaller  $\sigma_{SD}$ , for the same value of DM density.

*Effects on massive stars*— In principle, the accumulation of ADM particles inside massive stars should have the same effects as in low-mass ones, the transport effects of DM not depending (explicitly) on the burning mechanism (hydrogen via p-p or CNO). However, one crucial fact is to be stressed: transport effects start modifying dramatically the structure of a star when  $\epsilon_{trans}$  is of the same order of  $\epsilon_{nuc}$  within  $r_i$ . Two important things are to be noticed: *i*) the stellar luminosity scales non linearly with the stellar mass,  $L_* \propto M_*^{3.5}$ ; *ii*) the lifetime becomes shorter as the stellar mass increases. The latter, combined with the fact that the capture rate does *not* scale strongly with the stellar mass (roughly  $C \propto M_*$ ), leads to the conclusion that higher mass stars are less sensitive than low-mass ones to the same DM parameters. We have evolved models of increasing stellar mass between 1 and  $10M_{\odot}$  for the same ADM parameters, that we take  $\sigma_{SD}=10^{-37}\text{cm}^2$ ,  $\rho_{\chi}=10^7\text{GeV}/\text{cm}^3$ ,  $m_{\chi}=5\text{GeV}$ . The  $5M_{\odot}$  model gets out of the typical path on the HR at an age of approximately 90 Myr ( $X_c \sim 0.2$ ). Stars with masses larger than  $6M_{\odot}$  evolve normally, i.e. the impact of such ADM densities on their evolution is negligible.

This shows that stars with masses around the solar value -or even smaller, as in [13]- are better ADM probes than bigger ones, and yet this is good news, as approximately 60% of the stellar mass in our Galaxy is expected to be present in the  $0.1M_{\odot} \leq M_* \leq 1M_{\odot}$  range. In the

very same environment, low mass stars may be affected by the dramatic ADM effects, whereas more massive ones are insensitive to it.

It is also worth discussing the effects produced by this mechanism on the first stars to form in the Universe, the supposedly massive Population III. These objects should be naturally placed in very high DM density environments, as they are born at the center of a collapsing minihalo at high-redshift, and this is known to enhance DM effects onto such stars, [4, 5].

We have evolved a  $100M_{\odot}$  star with metallicity  $Z=10^{-4}$ , with increasing ADM densities, finding that for  $\sigma_{SD}=10^{-37}\text{cm}^2$  the effects illustrated throughout this paper show up at  $\rho_{\chi} \gtrsim 5 \times 10^{10}\text{GeV}/\text{cm}^3$ . Such densities are likely to be achieved in the very central regions of a primordial star forming halo [18]; yet, recent simulations of first star formation show a fragmentation of the proto-stellar core, thus yielding to both smaller stellar masses, and lower central DM densities [19]. Whereas no conclusions can be drawn at the level of the state of the art, it is worth to remark that the two effects may compensate each other, and PopIII may be indeed affected by ADM.

*Conclusions*— In this paper we have shown for the first time that feebly or non-annihilating DM, carrying weak interactions with the baryons, can have dramatic effects on solar mass, Main Sequence stars placed in DM environments denser than that of our Sun. This is due to the enhancement of DM-driven transport effects, that evacuate the nuclear energy produced in center of the core of the star. We have shown that once this happens this may provoke dramatic changes in the structure and external appearance of the star. We have shown that such dramatic effects take place in solar mass stars in environments with DM densities  $\rho_{\chi} \gtrsim 10^2\text{GeV}/\text{cm}^3$ , and that they can in principle be used as a probe for DM particle masses as low as  $m_{\chi}=5\text{GeV}$  and spin-dependent cross sections  $\sigma_{SD} \gtrsim 10^{-37}\text{cm}^2$ . Such parameter values are quantitatively comparable with those that could be placed by the failed observations of neutron stars in regions with this very same (fermionic) ADM density, see e.g. Figure 1 of [12], yet for as difficult as the observation of MS stars can be at the Galactic Center or ADM dense environments, they are less challenging than those of cold neutron stars.

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## Appendix

*Capture rate*— It is to be noticed that we compute the capture rate compute for the value  $\bar{v}=220$  km/s, and the  $\rho_\chi$  values we quote in the paper follow this particular choice for  $\bar{v}$  (typical of galactic velocity dispersion around the solar radius). However, the capture rate grows for decreasing  $\bar{v}$ , and it may therefore be useful to think the capture rate in terms of enhancement with respect to the solar capture; environments with  $\bar{v}$  lower than the one we adopt can in fact be easily found, e.g. above all: Dwarf Galaxies. For  $\rho_\chi=10^2\text{GeV}/\text{cm}^3$ ,  $\bar{v}=220$  km/s, the enhancement with respect to the solar capture is  $\sim 250$ , full formulae can be found in the Appendix of [9]. Self-interaction of DM particles can also provide a “boost” to capture, in [20].

*Numerical issues*— In spite of our efforts, we have not been able to fully understand the reason of the oscillations seen in Figure 3, whether they are a physical effect arising from the “bouncing” of the central temperature on the WIMP temperature floor, or a numerical artifact. We have however checked that the existence of oscillations does not affect our results nor does change our conclusions. Beside the theoretical consistency of the interpretation presented in the paper, one can be convinced of the actual physical consistency of our results with observations based on several numerical experiments we have performed: *a*), the deviation from the usual HR for mild DM densities takes place *before* oscillations start; *b*), in spite of the variation with timestep of the oscillations amplitude (shorter timestep, smaller oscillations), the tracks at varying timestep all converge in the same region of the HR; *c*), no mass loss is associated with oscillation, therefore excluding the hypothesis that they may drive the evolution of the object by (artificially, if they are a numerical artifact) changing its mass.